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LASER ANNEALING OF GaAs

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> Laser annealing of implanted semi-insulating GaAs has been accomplished by a ruby laser pulse ($\lambda = 0.694\mu m$, $t_p \approx 15ns$). Measurements of the electron concentration profiles in the Se^+ implanted and annealed GaAs samples indicate values in excess of $10^{19}/cm^3$, which are at least a factor of two higher than observed for correspondingly implanted samples which were thermally annealed.

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FOREWORD

The research covered in this report was carried out in the Integrated Circuits Group of the Rockwell International Science Center. The principal contributors were J. L. Tandon and F. H. Eisen. Experimental assistance was provided by E. Babcock.

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TECHNICAL SUMMARY

The goals of this program are to investigate the possibility of annealing implanted layers in GaAs using a laser, and to characterize the properties of these implanted and annealed layers. This section summarizes some of the results obtained during the first quarter of the program.

1. Irradiation from a pulsed ruby laser ($\gamma = 0.694\ \mu m$, $t_p \simeq 15$ ns) has been found to anneal implanted layers in semi-insulating GaAs with or without a Si_3N_4 encapsulant. The energy densities needed to achieve annealing conform to the values reported earlier.[4]

2. Ruby laser irradiation has no significant effect on semi-insulating GaAs in terms of changing its electrical properties.

3. Electrical activity measurements made on Se^+ implanted samples indicate significantly higher activation of Se^+ ions in laser annealed samples than in thermally annealed samples implanted with the same dose. This result is generally found to be true for high dose ($>10^{15}/cm^2$) implants.

4. Electron concentrations in excess of $10^{19}/cm^3$ were measured in the Se^+ implanted and laser annealed samples. This number is at least a factor of two higher than the highest electron concentrations obtained in the thermally annealed samples.[1]

1.0 INTRODUCTION

The desire to fabricate microwave devices/circuits has generated considerable interest over the last few years in the production of controlled, reproducible n-type layers in GaAs by ion implantation.[1-3] Unlike Si, currently the most widely used semiconductor material, ion-implantated GaAs has associated problems in the post-implantation annealing of the radiation damage. Because of the dissociation of GaAs at the high temperatures (>700°C) typically required for post-implantation annealing, thermal annealing of implanted GaAs usually has been carried out using an encapsulant (e.g., SiO_2, Si_3N_4, AlN, etc.) to prevent the escape of As. Although the escape of As can be largely prevented, significant out diffusion of Ga sometimes occurs through the encapsulant during thermal treatment. In addition, adherence of the encapsulant during the annealing is often a problem, which is a strong function of the technique used to deposit the encapsulant. Considering all these aspects of encapsulants, properties of thermally annealed implanted layers in GaAs are difficult to control and more difficult to understand.

In order to circumvent some of these problems with ion implantation in GaAs, the possibility of laser annealing ion implanted GaAs without an encapsulant seems attractive. The current contract aims primarily for such an effort. This first quarterly report details some preliminary results. Section 2 is a technical summary of achievements to date. The laser system setup that is being used to anneal implanted GaAs is described in Section 3. Section 4 contains an account of experiments conducted, with some interesting

5. Preliminary investigations indicate that implanted layers that have been made amorphous can be annealled better by laser irradiation than can partially crystalline or crystalline layers.

6. Electron mobilities in the high dose ($10^{15}/cm^2$) Se^+ implanted, laser annealed, layers are found to be quite poor when compared to the values measured in bulk GaAs.

results and possible interpretations. Future plans and possible line of experiments to be attempted are described in Section 5.

2.0 LASER SETUP

The laser setup for annealing implanted layers in GaAs uses a Korad oscillator and amplifier system. The block diagram of the system is shown in Fig. 1. The laser cavity consists of an oscillator with a ruby rod, a Q-switched Pockell cell, a Brewster polarizer, a totally reflecting mirror on one end and a partially reflecting mirror on the other end. The aperture in the cavity is used for obtaining a TEM_{00} mode of oscillation. The laser beam pulse generated in the cavity is expanded by a system of two lenses so that the resulting spot diameter is about 1 cm and is then amplified by the amplifier (see Fig. 1). The energy density of the pulse is primarily controlled by the bank voltage applied to the flash lamp that pumps the ruby rod in the amplifier. The system can put out pulses of about 15 ns duration with a good Gaussian spatial distribution.

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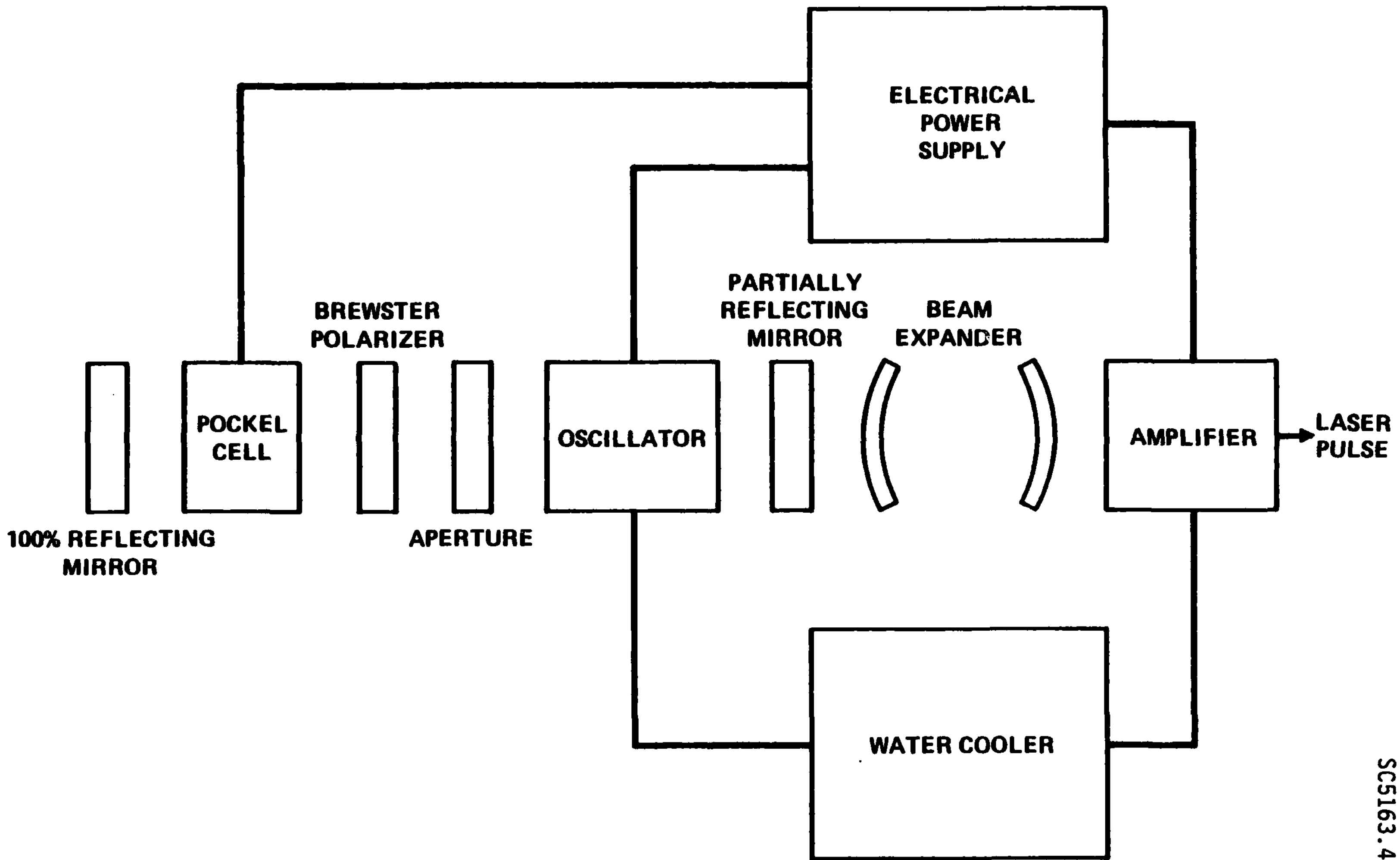

Fig. 1 The block diagram of the ruby laser setup used for annealing implanted GaAs.

3.0 ANNEALING EXPERIMENTS AND SOME PRELIMINARY RESULTS

This section describes the various experiments conducted to study the effect of laser irradiation on GaAs. Some of the results given here were presented at the Material Research society meeting on laser-solid interactions.(5)

3.1 Effect of Laser Irradiation on Semi-insulating GaAs

Various samples of <100> Cr-doped semi-insulating GaAs were irradiated with pulses from the ruby laser. The energy densities employed were in the range 0.4 - 1.2 J/cm^2. This range was similar to the range used in annealing implanted layers. Sheet resistance measurements made on the irradiated semi-insulating GaAs samples indicate no significant change in the sheet resistance after laser irradiation (typical decrease in the sheet resistance after laser irradiation was found to be less than a factor of two). Both qualified(6) and non-qualified substrates of semi-insulating GaAs retained their high sheet resistances ($>10^7 \Omega/$) even after laser irradiation.

3.2 Experiments on Annealing of Implanted Layers in Semi-insulating GaAs

Several semi-insulating <100> wafers of Cr-doped GaAs were implanted with 300 keV Se^+ ions at room temperature. The dose range selected was $3 \times 10^{12} - 1 \times 10^{15}$ Se^+ ions/cm^2. To minimize channeling during implantation, the ion beam was oriented at an angle of about 7° to the normal to the wafer surface. Laser annealing was accomplished in air by a Q-switched ruby laser pulse. The incident energy densities employed were in the range 0.8 - 1.2J/cm^2 in order to conform to the threshold annealing values observed in GaAs.(4)

Table I summarizes typical results of Hall-effect measurements made on some of the samples implanted with 10^{15} Se^+ ions/cm^2 and subsequently annealed thermally or by a laser pulse. The measurements were made after etching Van der Pauw type mesas provided with Au-Ge/Pt ohmic contacts.(1) The data in Table I show that better activation of Se^+ ions is achieved in the samples annealed by the laser, with or without a Si_3N_4 encapsulant, when compared to the sample annealed thermally. The measured effective sheet electron concentration (N_e) is significantly higher in the laser annealed samples when compared to the corresponding value in the thermally annealed sample, even though the thermally annealed sample was implanted at 350°C. This result could be due in part to the incorporation of Se atoms on substitutional sites in the GaAs crystal after laser or electron beam irradiation being higher than after thermal annealing. It should be noted, however, that all substitutional impurity atoms may not be electrically active in the GaAs crystal, as experiments conducted on bulk grown Te-doped GaAs and Te implanted GaAs[7,8] have indicated. Considering this possibility, significantly lower concentrations of compensating defects may also account for the higher values of N_e measured in the pulse annealed samples, when compared to the thermally annealed sample. The relatively low values of effective mobility (μ_e) found in the laser

TABLE I

COMPARISON OF THE SHEET-RESISTANCE (P_s), THE EFFECTIVE SHEET ELECTRON CONCENTRATION (N_e), AND THE EFFECTIVE MOBILITY (μ_e) FOR SEMI-INSULATING GaAs IMPLANTED WITH 300 keV 1 x 10^{15} Se^+ IONS/cm^2 AND ANNEALED THERMALLY, OR BY A RUBY LASER PULSE

	Thermal (350°C) AlN-900°C-10'-H_2	Ruby Laser (R.T.) 1J/cm^2 Si_3N_4 (1000A)	1J/cm^2 No Cap
P_s (Ω/)	130.5	143.2	130.3
N_e(cm^{-2})	3 x 10^{13}	1.9 x 10^{14}	1.4 x 10^{14}
μ_e(cm^2/vs)	1720	225	334

annealed samples (that is low in comparison to the thermally annealed sample) may be partially due to the higher density of ionized impurity centers in the laser annealed samples. Also, the laser annealed samples may contain certain small unannealed or partially annealed regions with residual ion damage due to the nonuniformities in the irradiated spot; these regions may contribute in lowering the mobility. From the data in Table I, it is interesting to note that satisfactory annealing of implanted GaAs can be accomplished using laser irradiation with or without an encapsulant. It should be mentioned, however, that visual inspections made under an optical microscope indicated the presence of blemishes on the surface of all laser annealed samples, with or without an encapsulant. The origin of these blemishes, which are probably indicative of nonuniform irradiation, and their possible influence on the electrical properties of the implanted and annealed layers is not understood at present.

It was observed that, with incident irradiation energy densities similar to those used to anneal the samples implanted with 10^{15} Se^+ ions/cm^2, no measurable electrical activity could be detected in the laser irradiated samples implanted with $< 10^{14}$ Se^+ ions/cm^2. This result indicates that low dose implants ($< 10^{14}$/cm^2) do not anneal as well as high dose implants (10^{15}/cm^2) when similar ranges of incident energy densities of laser pulse radiation are employed. It is interesting to note that the damage dose threshold for the formation of an amorphous layer in GaAs for room temperature 300 keV Se^+ implantation is estimated to be around 10^{14}/cm^2.[7] In this connection, the observed results imply that amorphous layers anneal better with pulsed laser irradiation than do crystalline or partially crystalline layers. A possible explanation for this may be that the laser beam pulse couples better with amorphous layers than with the crystalline layers, and therefore transfers the energy needed to anneal the implanted layers.

Figure 2 shows the depth profiles of the electron concentration (N) and of the electron mobility (μ) for the two laser annealed samples (see Table I). These profiles were obtained by successive stripping of surface layers combined with Hall-effect and resistivity measurements.[1] The LSS profile, calculated using a Gaussian approximation,[8] is also shown for comparison. The measured profiles show no correlation to the LSS profile in shape and they appear to be deeper than the range predicted by the LSS theory. This result is, however, not too surprising, as deeper profiles are also found in thermally annealed samples implanted with similar doses.[1] The evidence of higher activation measured in the sample which was laser annealed

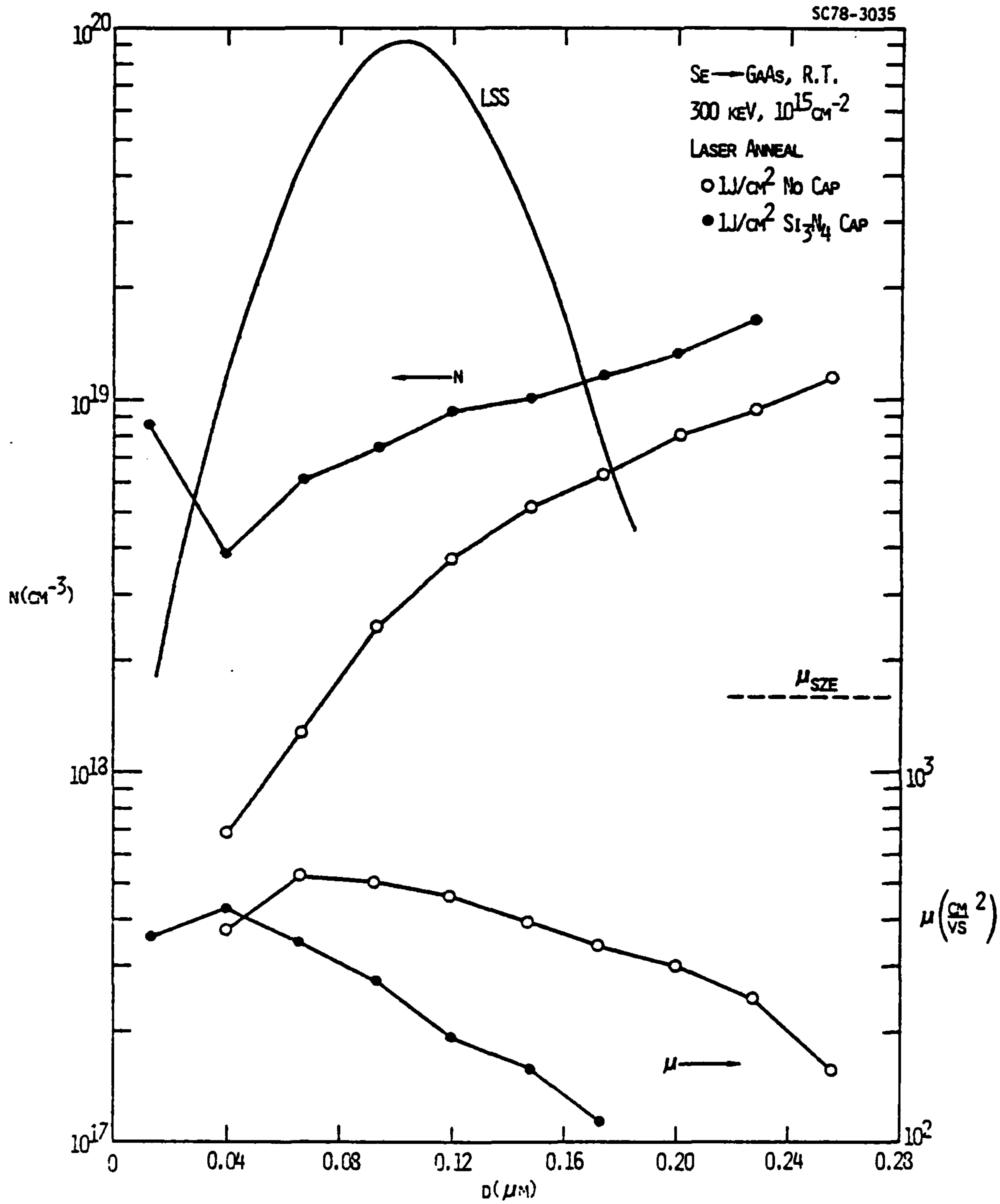

Fig. 2 Depth profiles of the electron concentration (N) and of the electron mobility (μ) measured in the two laser annealed samples (Table I), one annealed with and the other without a Si_3N_4 encapsulant. The incident energy densities employed were the same in the two samples.

with Si_3N_4 encapsulation, when compared to the sample annealed without an encapsulant, is not clear cut because of possible influence of non-uniformities as evidenced by the blemishes observed on the surfaces of both samples. Nevertheless, electron concentrations in excess of $10^{19}/cm^3$ are measured in both of the laser annealed samples, which is at least a factor of two higher than the concentrations measured in capped and thermally annealed samples[1] implanted with similar dose and energy of Se^+ ions. The mobility profiles in Fig. 2 show that the mobility is significantly lower in both of the laser annealed samples when compared to the values for bulk GaAs[9] for a similar range of peak electron concentrations.

4.0 FUTURE PLANS

In this section, future plans for carrying out experiments to investigate the mechanisms of annealing of implanted GaAs by laser irradiation are presented. It should be pointed out, however, that all of the ideas and thoughts presented here may not be implemented in the next quarter of the program. These plans should be viewed as long range plans in an attempt to explore and investigate the possibility of annealing implanted GaAs by laser irradiation.

(1) Design experiments to further investigate the possibility that amorphous layers anneal better than crystalline layers. These experiments would include annealing of hot (200°C) and cold (LN_2) implants by laser irradiation.

(2) Investigate the possibility of annealing implanted GaAs by laser irradiation with the sample mounted on a heated (<400°C) stage. Heating of GaAs may considerably change the optical properties of GaAs and thereby influence the absorption of laser energy.

(3) Initiate TEM measurements of implanted and laser annealed samples in order to study the defects in these samples.

(4) Try annealing experiments with another laser (e.g., a Nd-Glass laser, $\lambda = 1.06\ \mu m$).

(5) Obtain, wherever possible, a good comparison between the properties of laser annealed and thermally annealed implanted GaAs samples.

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